THE WORLD GRAIN ECONOMY AND CLIMATE CHANGE TO THE YEAR 2000: IMPLICATIONS FOR POLICY

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THE WORLD GRAIN ECONOMY AND CLIMATE CHANGE TO THE YEAR 2000: IMPLICATIONS FOR POLICY

REPORT ON THE FINAL PHASE OF A CLIMATE IMPACT ASSESSMENT

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FOREWORD

It is my pleasure to present the concluding report of a multi-agency, long-term, interdisciplinary study on the possible policy effects of climate change on world grain crops. The project was conceived in 1976 amid considerable concern about worldwide climatic trends and shrinking world food reserves. Given the importance of the global agricultural economy to international relations, and in particular the role of U.S. surplus production as a strategic asset, estimates of the effects of future climate change seemed useful—not only to the agricultural and scientific communities, but also to national policymakers. However, no acceptable method existed for projecting long-range climate change and its impact on crop yields. Stimulated by a research team from the Department of Agriculture, the National Defense University (NDU) became an organizing agency to coordinate this research.

I will not review the long history of this many-phased project. The results are amply documented in two earlier reports, *Climate Change to the Year 2000: A Survey of Expert Opinion* and *Crop Yields and Climate Change to the Year 2000.* These reports have gained wide acceptance in the scientific community, and have received favorable comment in technical journals and by such organizations as the American Association for the Advancement of Science. The methodology of this study was of special interest because of the use of a prototype climate-response model and the combining of futuristic and probabilistic techniques with expert opinion. This broke new ground in long-range forecasting. An unexpected development has been the interest of the public in this topic, evidenced by Government Printing Office sales of over 4,000 copies.

Another development, not totally unexpected, has been the relevance of study results to U.S. national policymaking. The study team anticipated that the research, although highly technical in its early stages, would ultimately have implications for national security. The team was pleased to note that the Carter administration's responses to the Soviet invasion of Afghanistan took cognizance of the conclusions of draft copies of the reports sent to high-level policymakers in key agencies. NDU is equally pleased that a draft of this concluding report is being integrated into the report of the Reagan administration's Global Issues Working Group.

The role of U.S. "food power" in U.S. policies remains unresolved, and this report is helpful to the continuing discussion. A major con-

clusion of the study is that the United States can consider its proper role in the world food situation for the rest of this century without great fear that major climatic change will significantly upset the calculations. This study provides the scientific base which enables planners to have at least some degree of confidence that their plans will not be undermined by climatic change.

In this concluding report, we must again express our appreciation to the individuals and organizations which participated in this project: the NDU research team; the Department of Agriculture; the National Oceanic and Atmospheric Administration; the Defense Advanced Research Projects Agency; the Institute for the Future; the climatologists and agricultural experts; and to Dr. D. Gale Johnson, University of Chicago, who was principal author of this final report.

Because of this effort, policymakers now have a basis upon which to consider the relationships between national security, agriculture, trade, and economics. And scientists have a precedent for projecting long-range climate change and crop yields. But perhaps the ultimate lesson of this long-term study is yet another reminder of the extraordinary scope and complexity of national security policymaking.

John S. Pustay

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SUMMARY

During the two decades preceding 1972, the United States and several other major exporting countries had problems with costly agricultural surpluses and excess production capacity. At the same time widespread hunger continued in many of the world's poorest countries. In 1972 the world food situation began to change rapidly and moved toward relative scarcities and high prices as the surpluses in developed countries disappeared, ushering in another period of recurring anxiety about the world's ability to feed its rapidly growing population. Pessimistic views of the future were widely publicized in popular media, with much attention being focused on the weather and its impact on world agriculture. Several prominent climatologists stepped forward to say that future world weather patterns were likely to become more unstable and less favorable. This view found a ready market. For example, in 1974 Fortune magazine published what was presented as an authoritative review, "Ominous Changes in the World's Weather," with a summary statement that "climatologists now blame those recurring droughts and floods on a global cooling trend. It could bring massive tragedies for mankind."

Although it referred to some disagreements among climatologists, the Fortune article clearly gave first place to a "grim scenario" associated with a global cooling trend seen as likely to result in southward shifts of the Sahara Desert, irregular monsoons during the rest of the century in regions such as northern India, negative impacts on the "highly specialized crop strains developed in the green revolution," and so on. Referring to theories that a number of ancient civilizations had been "undone not by barbarian invaders but by climatic change," Fortune soberly pointed out that "the world is too densely inhabited and politically divided now to accommodate mass migrations." The article went on to say that some climatologists were worried that powerful nations, particularly the Soviet Union, "may try to overrule nature through ill-considered engineering projects."

In 1976 the Central Intelligence Agency released a study with a gloomy prognosis for climate and its impacts. Later that year, National Geographic magazine published "What's Happening to Our Climate?"

Discussions about the facts of these matters, their interpretation, and relevant Government policies were carried on among scientists, the general public, and Government officials. Some critics severely scolded Government analysts and policymakers for not tak-

ing into account the insights of certain climatologists in designing U.S. programs and policies for agriculture, food, and foreign assistance.

Because of the key role the United States was playing in the world food situation, the implications of possible climate changes were seen to be directly related to the national security of the United States. Discussions among personnel in the Research Directorate and the faculty of the National Defense University (NDU) led to a conclusion that U.S. policymakers and the public needed a study putting together the available scientific information and expert judgments on possible climate changes and their impacts on the world food situation to provide a basis for considering alternative policies and programs.

These discussions soon revealed that several Government agencies were interested in the problem and were prepared to contribute resources and expertise. In the fall of 1976 a research study was begun, sponsored jointly by NDU, the Department of Agriculture, and the National Oceanic and Atmospheric Administration, to quantify the likelihood of significant changes in climate and the practical consequences for world food problems and relevant U.S. policies. A small, interdisciplinary staff was set up in the Research Directorate at the University. An advisory group of eminent scientists and administrators was asked to provide guidance. A contract with the Institute for the Future, Menlo Park, Calif., to provide advice and technical assistance was financed under the auspices of the Defense Advanced Research Projects Agency. Leading scientific experts on climate and agriculture agreed to participate in the study.

The NDU Research Staff soon realized that the climatologists' inputs had to be obtained by a careful opinion survey. The science of climatology has not developed to the point at which well-established and verified theories exist that can objectively forecast climate changes, so the staff began to seek, from those who were thoroughly familiar with the state of research and knowledge, judgments as to the likelihood of occurrence of certain well-defined climatic events in the future. This procedure was in no sense an attempt to substitute judgment for hard science. It merely recognized the importance of obtaining the best possible judgments for the use of policymakers with regard to present issues. The alternative—postponing policy decisions indefinitely until science progressed to the point of providing more thoroughly researched answers—was unacceptable. As a consequence, a survey of expert climatologists' opinions was designated as Task I of the study. The results were published by NDU in February 1978 as *Climate Change to the Year 2000.*

A similar problem with the present state of science faced the research group in its communications with agricultural experts concerning possible effects of climate change on crop yields. A survey of a panel of agricultural experts and an analysis of the results constituted Task II, published in 1980 as *Crop Yields and Climate Change to the Year 2000*. In Task III, the results of which are presented in this volume, a team of leading agricultural economists used a previously published econometric model of world agricultural production, consumption, and trade to explore the possible impacts on world markets of the alternatives developed by the panels of climatologists and agriculturists.

The staff believed that the judgments of the experts had to be put in the form of probability statements concerning alternative futures. The rational weighing of alternatives requires that judgments on the likelihood of alternatives be clearly stated. This need was recognized and accepted by the panels of expert scientists, although the concept generated initial uneasiness among some. In fact, a few scientists refused to cooperate in the research because they were concerned that such judgments on the probabilities of future events would not be scientifically respectable or would be subject to misuse.

The views elicited from the climatologists were analyzed in terms of five possible climate scenarios for the rest of the century. The scenarios were designated as Large Cooling, Moderate Cooling, Same as the Last 30 Years, Moderate Warming, and Large Warming. Based on the views of the climatologists, the probabilities of occurrence of the five scenarios were judged to be 0.10, 0.25, 0.30, 0.25, and 0.10, respectively.

Thus the panel of climatologists collectively viewed the overall odds as being 0.80 (or 8 out of 10) that the world will experience either no change in climate or only a moderate warming or cooling by the end of the century. The analysis in Task III estimates that the impact of such moderate changes in climate on production of grain in the world as a whole would be very small—less than a 0.2 percent net change in world grain production. World grain trade patterns would not be greatly affected. Significant variations in grain trade would be confined to the United States, Canada, and the Soviet Union. Grain prices would be affected very little.

The more extreme Large Cooling and Large Warming scenarios were judged by the climatologists to have a probability of occurrence of only 0.10 (or 1 out of 10) each. But even if one of these scenarios should occur, the net effects on world grain production, prices, and trade would be moderate, with some countries being helped and others harmed. The United States would have relatively

large exports under the Large Cooling scenario (about the same as under Moderate Cooling) and relatively low exports under a global warming; however, the percentage changes would be small. The Soviet Union's grain trade would be affected significantly with a shift from exports under warming to substantial imports under cooling, depending on the extent to which they chose to offset shortfalls in production by imports.

The main conclusion of this study is that through the end of this century the world is very unlikely to face climate changes of such magnitude as to affect the world food situation significantly. United States food policy would have to be modified if there were a widely accepted view of imminent and highly probable major changes in world climate. Changes in the world's climate that would significantly affect the needs of other countries for commercial food shipments and food aid, and at the same time would modify the United States' capacity to fulfill such needs, could have an impact on the U.S. balance of payments, inflation, and the welfare of U.S. consumers. A major issue discussed in the past several years and currently of concern is whether the United States possesses "food power" that could be used to further its strategic position relative to other countries such as the Soviet Union or the members of the Organization of Petroleum Exporting Countries (OPEC)

If the United States were faced with highly probable, major, climate-induced shifts in its position vis-à-vis the world food situation, then the Government should immediately consider making changes in agricultural price support and acreage control programs, programs for storage and disposal of stocks of commodities, attitudes toward international trade controls and negotiations, agricultural scientific research programs, investment in dams and land development, food aid, and technical and financial assistance for agricultural development in the poor countries. *The significance of this study is that the United States can consider its proper role in the world food situation without great concern that climatic changes during the rest of this century will upset its calculations.*

The comfort of this conclusion must, of course, be qualified. As emphasized above, it is a probabilistic view, based on judgments and limited scientific evidence. It could be wrong. We should encourage scientists to seek more evidence, and we must be alert to evaluate it. Also, the study focused only through the end of this century. Much of the recent discussion of climate change has shifted to concern about possible carbon dioxide "greenhouse effects" some years into the next century. The methodology developed in this study could be applied to that and similar problems.

CHAPTER ONE

BACKGROUND AND METHODOLOGY

INTRODUCTION

This report is the third and final phase of a research effort to quantify expert perceptions of global climate change to the year 2000 and to assess the potential effects of those perceived changes on the yield, production, and prices of major world food crops. Task I defined and estimated the likelihood of changes of climate during the last quarter of the 20th century and constructed climate scenarios for the year 2000.[1] Task II estimated the effects of possible climate changes upon the yields of selected crops in specific countries and developed a methodology for combining crop responses and climate probabilities into climate-crop scenarios for the year 2000. Task III evaluated the domestic and international policy implications of the climate-crop scenarios.[2] This report gives the economic analysis and conclusions for Task III and is based directly upon the results of Tasks I and II.

THE CLIMATE SCENARIOS OF TASK I

The five climate scenarios for the year 2000 were called Large Cooling, Moderate Cooling, Same as the Last 30 Years, Moderate Warming, and Large Warming. Based on the responses of the climatologists, the respective "probabilities" of occurrence of the scenrios were 0.10, 0.25, 0.30, 0.25, and 0.10. We are not dealing here with certainties. No one has the knowledge to predict precisely how much warmer or cooler the world (or any specific part of it) will be at any future date.

The Task I findings most relevant to our purposes are the long-term changes in mean temperatures ($\Delta\bar{T}$) and precipitation ($\Delta\bar{P}$) judged likely in each scenario for the five zones of latitude treated in the study. These climate-change variables are shown in table 1, along with the country-crop combinations that were studied in Task II and the latitude zones to which they were assigned. Since none of the selected country-crop combinations fell in the higher middle latitudes of the Southern Hemisphere, the climate-change variables for this latitude zone have been omitted.

The No Change or base case used in Task III differs from the Same case scenario in table 1. The Same as the Last 30 Years

Table 1

CLIMATE PARAMETERS BY LATITUDINAL ZONES

Latitude	Hemisphere	Crop: Corn	Crop: Rice	Crop: Soybean	Crop: Spring Wheat	Crop: Winter Wheat	Large Cooling $\Delta\bar{T}$	Large Cooling $\Delta\bar{P}$	Moderate Cooling $\Delta\bar{T}$	Moderate Cooling $\Delta\bar{P}$	Base $\Delta\bar{T}$	Base $\Delta\bar{P}$	Moderate Warming $\Delta\bar{T}$	Moderate Warming $\Delta\bar{P}$	Large Warming $\Delta\bar{T}$	Large Warming $\Delta\bar{P}$
Higher Middle	N				Canada U.S. U.S.S.R.	U.S.S.R.	−1.05	−2.0	−0.50	−2.0	−0.25	0.0	+0.65	+2.0	+1.40	+6.0
Lower Middle	N	U.S.		U.S.		P.R.C. U.S.	−0.85	+2.0	−0.35	0.0	+0.25	0.0	+0.45	0.0	+1.0	+2.0
	S	Arg.				Arg. Austral.	−0.95	+2.0	−0.20	0.0	+0.15	0.0	+0.45	0.0	+1.0	+2.0
Sub-Tropical	N		India P.R.C.			India	−0.50	−2.0	−0.30	−2.0	+0.20	0.0	+0.40	0.0	+0.75	+2.0
	S			Brazil			−0.50	−2.0	−0.20	−2.0	+0.15	0.0	+0.40	0.0	+0.75	+2.0

Expected Change in Mean Temperature and Mean Precipitation in Five Climate Scenarios

scenario—the most probable one—delineates a slight global warming. By contrast, the No Change or base case in the present report is assumed to be a persistence of recent climate, that is, literally no change from the climate prevailing in 1976, the date of the climate questionnaire. Moreover, since the Same scenario of Task I was projected to have negligible effects on average crop yields (1 percent or less except for a −1.2 percent effect on Indian wheat), we have equated the probability of the Same scenario (0.30) with the probability of the base or No Change scenario in Task III.

Although additional climatological data were solicited in Task I, the climate scenarios were defined in terms of two variables—temperature and precipitation. Temperature is measured in terms of changes in degrees Celsius from the average level for 1970–75 ($\Delta\bar{T}$), while precipitation is measured in terms of percentage change from the average for 1941–70 ($\Delta\bar{P}$). The majority of the zonal climate scenarios involve either no change in precipitation or a slight increase. The exceptions are the cooling scenarios for the higher middle latitudes of the Northern Hemisphere and the subtropical latitudes for both hemispheres.

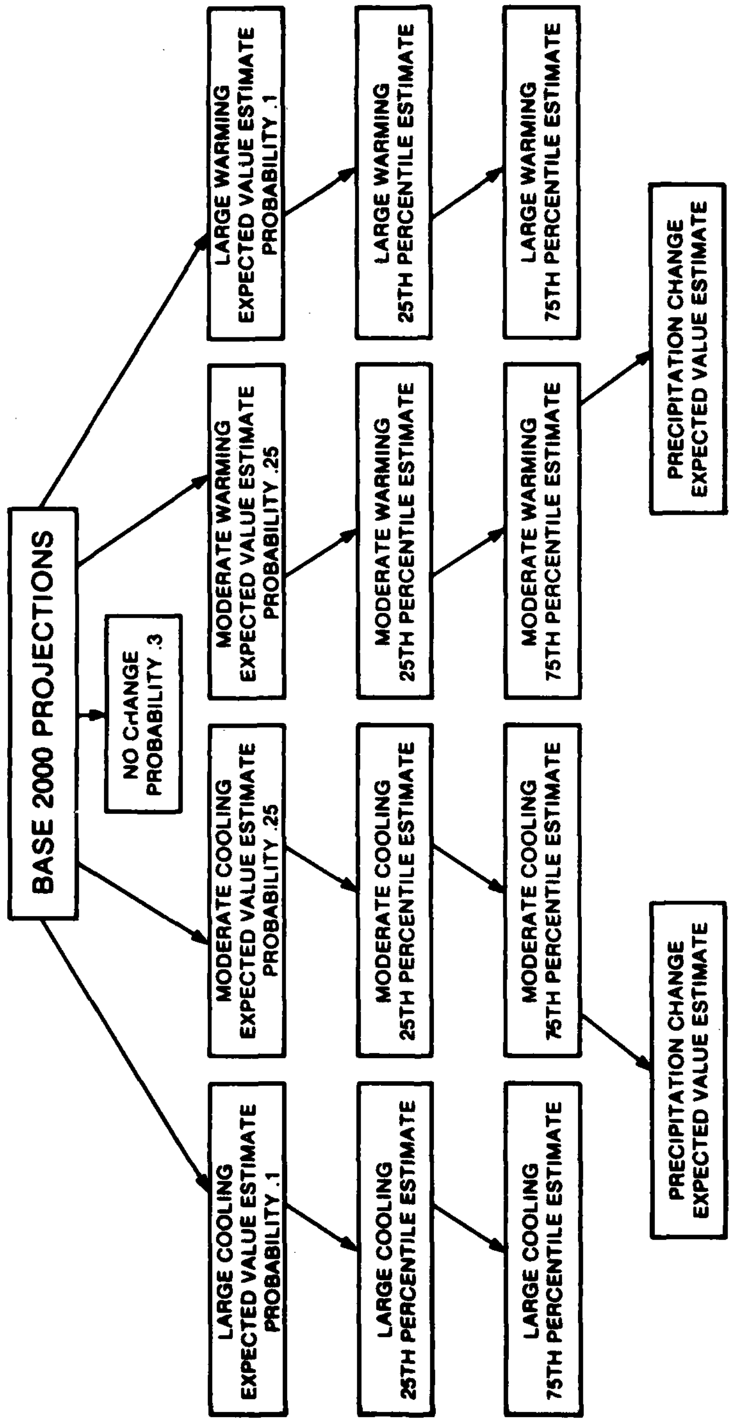
Figure 1 indicates the five basic scenarios and excursions analyzed in this report. The top part of the figure indicates the "probabilities" derived for the five scenarios in Task I. The largest probability, 0.30, is for the No Change scenario, whereas the Moderate Cooling and the Moderate Warming scenarios have slightly lower probabilities of 0.25. The more extreme climate changes have probabilities of 0.10. This report first considers the expected-yield estimates of the scenarios; later the report analyzes and discusses the alternatives presented in the bottom three rows of figure 1.

THE CLIMATE-CROP SCENARIOS OF TASK II

The agriculture panelists enlisted for Task II were asked to make point estimates of the changes in crop yields that could be expected for various combinations of departures of annual temperature and precipitation from their averages in the base period (the recent past). The yield estimates were to be expressed as percentages of the yields for years with average weather. Averages of the responses, weighted by the expertise of the respondents, were then calculated to determine relative yield as a function of annual crop weather, that is, temperature and precipitation. These crop-yield estimates were made on the assumption of *no change from the technology currently in use in the country for the specific crop.* To make meaningful comparisons between crops, the yield functions were normalized to express annual yield as a percentage of the average in the base period. For the purposes of this normalization, the ob-

Figure 1

SCENARIO DIAGRAM



served base period distribution of annual crop weather was approximated by a bivariate normal distribution.

The Task II respondents were also asked to give their best estimates of the effects of changes in technology on the trend in crop yields for the period 1976–2000. These estimates were made assuming that there would be *no change in climate.*

For each country-crop combination, a probability distribution of relative annual yields was developed for each climate scenario. Since crop weather varies from year to year *within* each climate scenario, there is considerable overlap of possible annual yields from one scenario to another. Although the report of Task II, Crop Yields and Climate Change to the Year 2000, should be consulted for full details, figures 2 and 3 illustrate the method used and the resulting distribution of yields for the five scenarios for U.S. corn.

Figure 2 gives the relative yield contours for a range of annual temperature and precipitation combinations. The contour lines are based on the weighted average of the respondents' estimates of the annual yield for each temperature and precipitation combination. A *discrete* climate-response model was employed in Task II, that is, both yield as a function of annual crop weather and the interannual variability of crop weather were expressed in matrix form; the continuous annual-yield function in figure 2 was derived from the annual-yield matrix for U.S. corn.[3] The data in figure 2 were used to translate the specifications of the climate scenarios into projected distributions of annual yields.

Although table 1 gives the changes for each climate scenario in *average* annual temperature and precipitation from the base period, annual temperatures and precipitation within any one scenario will deviate from the averages. The year-to-year fluctuations of temperature and precipitation will induce a distribution of annual yields. As outlined in appendix B, one can calculate such a yield distribution (figure 3), taking into account, for example, the long-term climate shift of the Large Warming scenario (table 1), the annual-yield function in figure 2, and the historical variability of annual temperature and precipitation in the U.S. corn belt.

Task II used three statistics from each of these yield distributions. The core analysis of the five climate scenarios utilized the expected value or expected yield, that is, the projected average annual yield, which is 97.5 percent of the average yield in the base period. The 25th and 75th percentiles were used in alternative Task III excursions that examine the sensitivity of the economic model to the crop-yield assumptions. The other excursions were based on the expected yields associated with positive and negative 10 percent changes in annual precipitation (but no change in temperature).

Figure 2

U.S. CORN

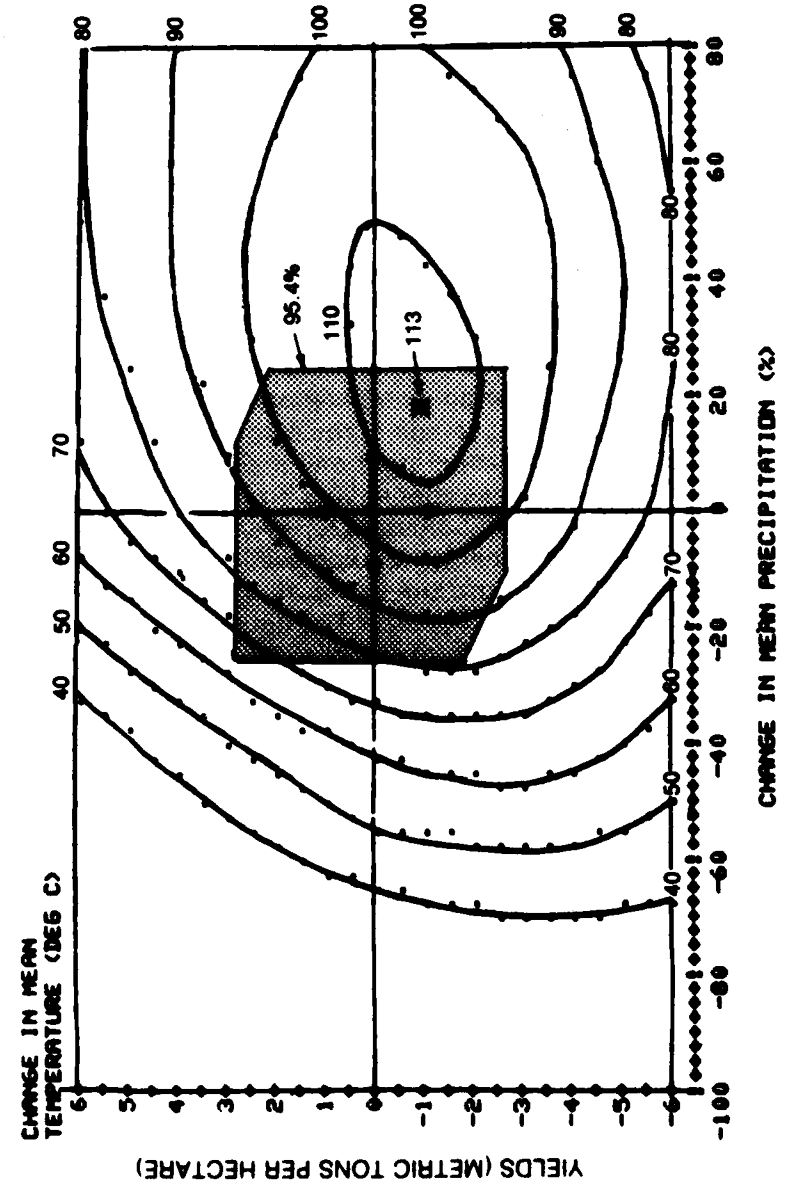
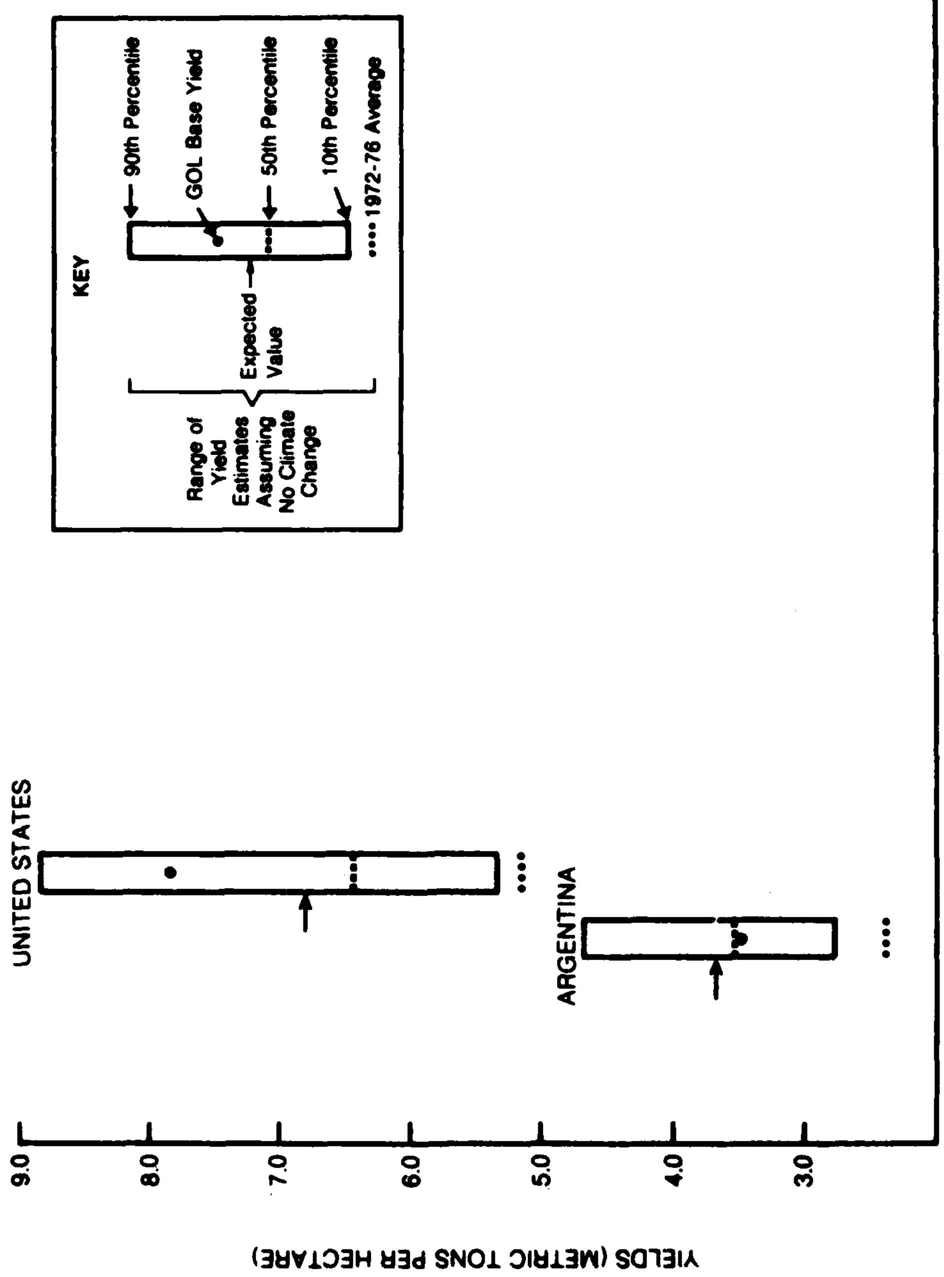


Figure 3

PROJECTED BASE 2000 YIELDS FOR CORN
(Task II Questionnaire Results and GOL Model Base 2000 Yields)



THE GOL ECONOMIC MODEL OF WORLD AGRICULTURE

The expected-yield estimates from Task II are basic ingredients for Task III. They were used as inputs by the U.S. Department of Agriculture in its Grain-Oilseed-Livestock (GOL) Model to project the supply and demand for grain and soybeans for the year 2000.[4] For the purposes of Task III, several changes were made in the GOL Model. These changes included extending the time to the year 2000 and modifying some of the trend data for population and per capita income growth based on more recent projections.

We had to supplement the yield estimates from Task II to account for a larger percentage of the world's grain output. Task II provided climate-induced yield changes for country-crop combinations that comprise approximately 45 percent of world production. These combinations are indicated in the top panel of table 2. The second panel indicates the combinations for which climatic effects were estimated through comparisons with the results of Task II. For the country-crop combinations of Task II, we used regression analyses to fit specific yield equations in which yields were a function of prices, fertilizer use, use of high-yielding varieties, changes in planted area, time, and an error term to develop other important contributions. We assumed that the error term was a reasonable measure of the sensitivity of yield to weather changes. This assumption and the Task II results were used to extend the analyses both within and across countries.

For example, a high degree of positive correlation between the Soviet wheat error terms and the barley error terms allowed us to extend the Task II analysis of wheat to Soviet coarse grains. We could also correlate errors across countries; such correlations permitted the extension of the Argentine and Australian wheat and corn results to South Africa. By this process, 27 additional country-crop combinations were developed to account for roughly 50 percent more of the world's grain and soybean production.

There remained approximately 5 percent of world production for which the error analysis was inappropriate. We assumed for the country-crop combinations listed in the third panel of table 2 that climate change would have no effect on yields, production, trade, and prices. The assumption is most likely a reasonable one because of the offsetting effects of warming and cooling in the areas of Africa, Latin America, and East Asia.

Table 2

SOURCES OF CLIMATE CHANGE IMPACT ESTIMATES

I. Estimates of Impact of Climate Change Based on Task II Questionnaire (45% of World Production)

1. U.S. wheat (spring and winter)
2. U.S. corn
3. U.S. soybeans
4. Canadian wheat
5. Australian wheat
6. Soviet wheat (spring and winter)
7. Chinese wheat
8. Chinese rice
9. Argentine wheat
10. Argentine corn
11. Indian wheat
12. Indian rice
13. Brazilian soybeans

II. Estimates of Impact of Climate Change Based on Yield Error Analysis (50% of World Production)

1. U.S. coarse grain
2. Canadian coarse grain
3. Western European wheat
4. Western European coarse grains
5. Eastern European wheat
6. Eastern European coarse grains
7. Australian coarse grain
8. South African wheat
9. South African coarse grain
10. Soviet coarse grain
11. Chinese coarse grain
12. Middle American wheat
13. Middle American coarse grain
14. Brazilian coarse grain
15. Argentine coarse grain
16. North African/Middle Eastern wheat (High Income)
17. North African/Middle Eastern coarse grain (High Income)
18. North African/Middle Eastern wheat (Low Income)
19. North African/Middle Eastern coarse grain (Low Income)
20. Indian coarse grain
21. Other South Asian wheat
22. Other South Asian coarse grain
23. Other South Asian rice
24. Thai coarse grain
25. Thai rice
26. Other East Asian rice
27. Indonesian rice

III. Major Regions with No Estimates of Impact of Climate Change (5% of World Production)

1. Central African coarse grain
2. East African coarse grain
3. Andean coarse grain
4. East Asian rice
5. East Asian coarse grain

CHAPTER TWO
THE ESTIMATED AGRICULTURAL EFFECTS OF THE FIVE CLIMATE SCENARIOS

INTRODUCTION

The intermediate objective of Task III was to estimate the differential impacts of the climate scenarios on important economic variables as of the year 2000. We must emphasize that the objective of Task III was not to project likely *absolute* levels of world food production, consumption, and trade or to comment on the likely adequacy of world grain or food supplies in the future. Although we believe that the modified trend assumptions used in the analysis of the base projections for the year 2000 were reasonable for the purposes of estimating the *differential* effects of climatic differences, our results should not be used to answer other questions.

YIELD EFFECTS

Table 3 represents the variations in grain and soybean yields from the base or No Change scenario for the four expected-value climate-change scenarios.[5] These estimates were read from the expected-value (roughly 55th percentile) point on the Task II scenario-specific probability distributions describing the impact of climate change on annual yields. To give some perspective with respect to the expected-yield variations for the climate scenarios, the last column shows the coefficient of variation of annual yields for the period 1950–77. The expected-yield variations for the climate scenarios are considerably smaller than the coefficients of variation for the historical annual-yield data. However, not too much emphasis should be given to this comparison. Presumably under each of the climate scenarios variations of annual crop yields of the general order shown in table 3 would continue. The expected-yield variations given for each scenario represent expected long-run differences in yields and thus have implications different from annual fluctuations of yields. Storage, for example, can be used to reduce the variability of consumption when production varies from year to year, but it would not be an appropriate tool to offset the differences in the expected yields due to climatic change.

The results in table 3 indicate that the four climate-change scenarios are projected to have significant differential effects upon certain

Table 3

VARIATIONS IN GRAIN YIELDS FROM BASE PROJECTION LEVELS UNDER ALTERNATIVE CLIMATE SCENARIOS

(Expected Value Estimates of Impact of Climate Change on Crop Yields)

Crop/country	Scenarios: Large cooling	Scenarios: Moderate cooling	Scenarios: Moderate warming	Scenarios: Large warming	Historic inter-annual variation[1]
	Percent variation from Base 2000 levels				
Developed Countries					
United States					
Spring wheat	−.96	−1.01	+.10	+.28	
Winter wheat	+2.60	+.59	−1.08	−1.21	
All wheat	+1.71	+.19	−.79	−.84	±8.2
Coarse grains	+2.33	+.74	−1.40	−2.52	±9.5
Canada					
All wheat	−8.48	−4.31	+3.78	+7.88	±17.5
Coarse grains	−4.75	−2.42	+2.11	+4.41	±9.8
European Community					
All wheat	+.67	+.13	−.45	−.69	±5.9
Coarse grains	+.96	+.23	−.51	−.86	±5.7
Other Western Europe					
All wheat	+.98	+.19	−.66	−1.01	±8.6
Coarse grains	+1.06	+.25	−.56	−.95	±6.3
Australia					
All wheat	+5.46	+.94	−2.49	−4.30	±15.4
Coarse grains	+4.54	+.79	−2.06	−3.56	±12.7
South Africa					
All wheat	+2.90	+.50	−1.31	−2.27	±8.2
Coarse grains	+11.10	+1.77	−4.27	−6.32	±22.9
Centrally Planned Countries:					
Eastern Europe					
All wheat	−1.19	−.23	+.80	+1.23	±10.5
Coarse grains	−1.21	−.29	+.64	+1.09	±7.2
USSR					
Spring wheat	−6.41	−3.74	+3.06	+6.74	
Winter wheat	−6.17	−3.40	+2.91	+6.09	
All wheat	−6.30	−3.60	+3.00	+6.47	±15.4
Coarse grains	−5.60	−3.17	+2.65	+5.71	±16.8
China					
All wheat	−1.28	−.86	+.40	+1.52	±10.3
Coarse grains	−1.61	−1.09	+.49	+1.89	±6.0
Rice	−.81	−.77	−.56	−.56	±5.4
Developing Countries:					
Indonesia					
Rice	−.49	−.62	−.49	−.19	±4.5
Thailand					
Coarse grains	+10.48	+1.66	−4.02	−5.95	±21.5
Rice	−.65	−.83	−.65	−.26	±6.0

Table 3

VARIATIONS IN GRAIN YIELDS FROM BASE PROJECTION LEVELS UNDER ALTERNATIVE CLIMATE SCENARIOS—Continued

(Expected Value Estimates of Impact of Climate Change on Crop Yields)

Crop/country	Scenarios: Large cooling	Moderate warming	Moderate cooling	Large warming	Historic inter-annual variation[1]
	Percent variation from Base 2000 levels				
Other Southeast Asia					
Rice	−.54	−.68	−.54	−.21	±5.0
India					
All wheat	+1.61	+.56	−2.59	−3.99	±9.7
Coarse grains	+.99	+.34	−1.61	−2.47	±6.0
Rice	−.79	−1.00	−.79	−.31	±7.3
Other South Asia					
All wheat	+1.55	+.53	−2.45	−3.80	±9.4
Coarse grains	+.54	+.19	−.89	−1.36	±3.2
Rice	−.49	−.62	−.49	−.19	±4.5
High Income North Africa/Middle East					
All wheat	+3.30	+.57	−1.55	−2.73	±10.3
Coarse grains	+3.51	+.61	−1.65	−2.90	±11.0
Low Income North Africa/Middle East					
All wheat	+3.45	+.59	−1.62	−2.86	±10.8
Coarse grains	+2.63	+.45	−1.23	−2.18	±8.2
Middle America					
All wheat	+3.05	+.57	−1.53	−2.69	±10.7
Coarse grains	+3.16	+.50	−1.21	−1.80	±6.5
Brazil					
Coarse grains	+2.31	+.37	−.89	−1.31	±4.7
Argentina					
All wheat	+4.13	+.78	−2.08	−3.65	+14.5
Coarse grains	+5.11	+.81	−1.96	−2.90	+10.5
All grain weighted Total above[2]	−.40	−.61	+.22	−.14	±9.2
All grain world Total[3]	—	—	—	—	±3.1

[1]Coefficient of variation from fitted 1950–1977 equations.
[2]Production weighted.
[3]World grain yield series.

country-crop combinations. For example, cooling would have a significant adverse effect upon grain yields in Canada and the Soviet Union, while warming would have positive effects in those countries. Cooling would have a significant positive effect on yields in Argentina, North Africa, Australia, and Middle America, and on coarse-grain yield in Thailand. The United States would also gain, though the yield effect for spring wheat indicates that the northern parts of the United States would probably be adversely affected by cooling.

The projections for rice have an interesting pattern. In every projection, any departure from the base or current-climate scenario would result in a small decline in rice yields. However, the general pattern of the yield projections indicates that the relatively large effects of climatic change would be felt by high-income countries and that the low-income countries, except for Middle America, would be little affected.

The next-to-last row of table 3 shows the weighted yield effects of the four scenarios for all the country-crop combinations included. Large Cooling is projected to reduce average yields by 0.40 percent, and Moderate Cooling by 0.61 percent. Moderate Warming is the only scenario that is projected to increase average yields, and that by only 0.22 percent; Large Warming would presumably have a small negative effect of 0.14 percent.

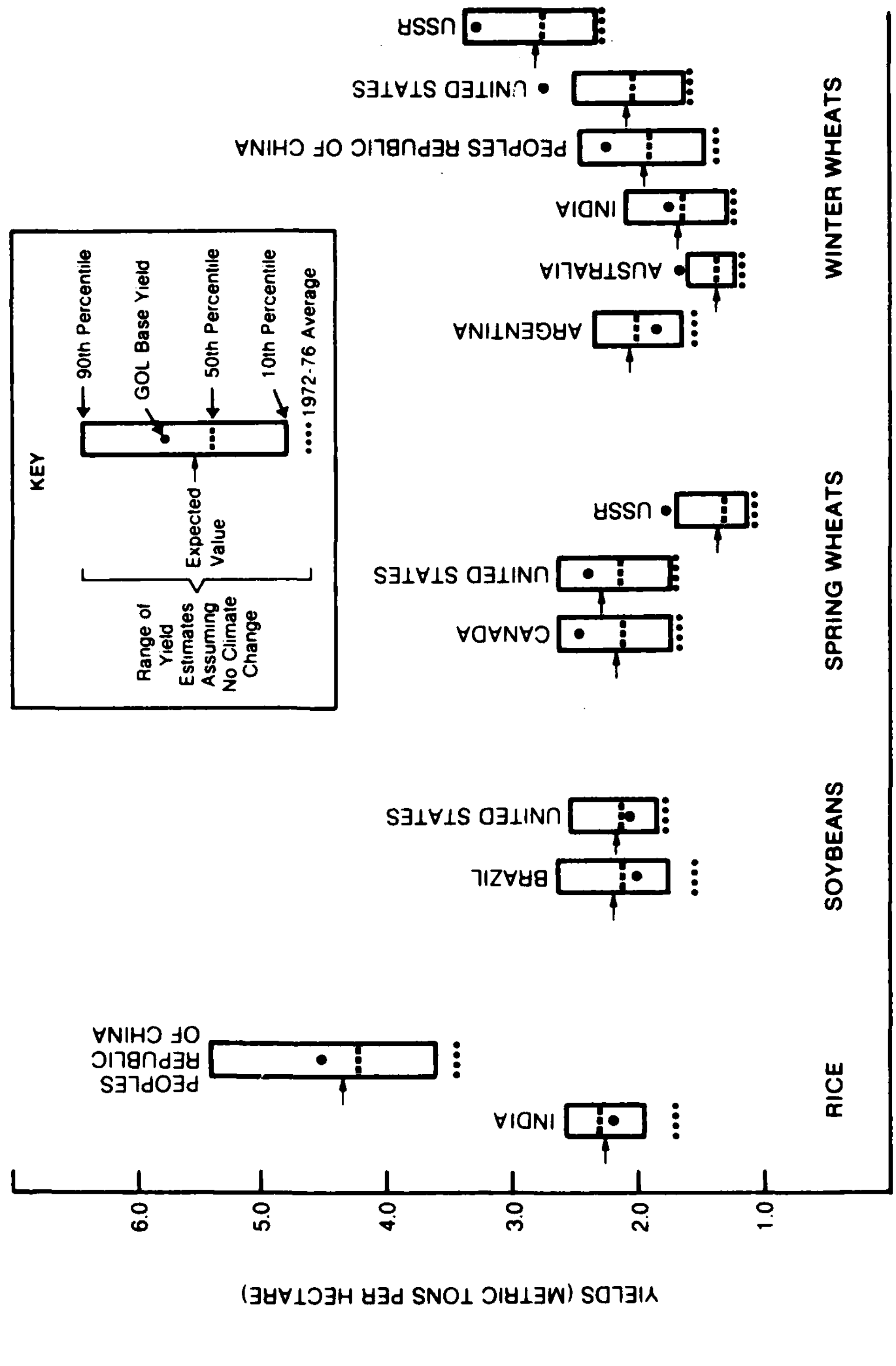
PRODUCTION EFFECTS

The respondents to the Task II questionnaire were asked to project absolute yields for the year 2000 base scenario. The projected yields were to reflect the effects of changes in technology and knowledge on grain yields under the assumption of no change in climate. Such projections were made for the 15 country-crop combinations examined in Task II.

The technological projections of Task II were not used in Task III. The yields used in the GOL Model were derived from yields trends, generally for the period 1955–76, and in most cases from country- and crop-specific analyses of input use and rates of technology adoption. The differences in the yields projected for the year 2000 are shown in figure 4. Other information is also provided, including the 1972–76 average yield as well as the 10th, 50th, and 90th percentiles of the aggregated distributions of yields projected by the panelists in Task II. As indicated by the key, the single arrow gives the projected yield derived from Task II, and the dot gives the yield used in the GOL Model.

The more important differences between the yields from Task II and the GOL Model may be noted. The largest differences are for corn

Figure 4
PROJECTED BASE 2000 YIELDS
(Task II Questionaire Results and GOL Model Base 2000 Yields)



in the United States, spring and winter wheat in the Soviet Union, and winter wheat in the United States. Somewhat smaller differences exist for Chinese winter wheat and Canadian spring wheat.

The projected increase of U.S. corn yields used in the GOL Model may seem large, but the average annual growth rate from 1975–77 levels is less than 1.4 percent, compared with the 3.4 percent growth rate for the previous 25 years. U.S. interagency yield committee estimates reach the year 2000 level of Task II by 1985–90. Since the 1978 corn yield in the United States was 6.3 metric tons per hectare, it can be argued that the yield of approximately 6.8 tons projected in Task II is likely to be on the low side. Admittedly, growing conditions in 1978 were favorable, but the projected Task II yield for the year 2000 of only some 8 percent over a yield already achieved implies that nearly all yield-increasing potentialities have been exhausted for U.S. corn. Many Task II panelists alluded to the then-acute energy crisis as a reason for a slowdown in technological enhancements of crop yields.

The yield projections in the GOL Model are intended to reflect possible yields if base climate prevailed and if technology were at a given level. However, since factors other than climate and technology affect yields, the yields implicit in the production projections may differ from the yields introduced into the model. The yields that emerge from the production projections are intended to be long-run equilibrium yields, and they depend on numerous variables that are included in the model but were not explicitly addressed in Task II. Among the more important variables are the prices of farm products, prices of farm inputs, the availability of land for each major crop, and the quality of the land planted to each crop. We cannot infer directly from the yields introduced into the GOL Model how production under the four alternative climate-change scenarios will vary from the base scenario. Not only will yields be influenced by other variables, but changes in the area devoted to a particular crop or the quantity of inputs used in its production may offset some of the yield variations attributed to climate in Task II.

Table 4 presents the results of the GOL Model runs for crop production in the year 2000 for the five climate scenarios. The table gives the production variations in thousands of metric tons for the four climate-change scenarios relative to the base scenario. Table 5 presents the same data but in terms of percentage changes. The countries are arranged in the table in two ways: first, in the three categories of developed countries, centrally planned economies, and developing countries; and second, according to the positive effects of cooling or warming. The cooling countries, for example, are

Table 4

VARIATIONS IN GRAIN PRODUCTION (TONS) FROM BASE PROJECTION LEVELS UNDER ALTERNATIVE CLIMATE SCENARIOS

(Expected Value Estimates of Impact of Climate Change on Crop Yields)

Crop/country	Scenarios				
	Large cooling	Moderate cooling	Projected base level	Moderate warming	Large warming
			1,000 in tons		
I. Developed Countries:	+1,803	+206	682,982	−10,529	−16,550
United States	+5,973	+4,692	389,088	−7,698	−14,680
Canada	−8,680	−3,715	63,278	+882	+3,799
European Community	+380	−1,142	126,407	−2,270	−2,782
Other Western Europe	+277	−307	50,010	−810	−1,022
Oceania	+1,513	−153	31,625	−202	−945
South Africa	+2,520	+831	22,574	−431	−920
II. Centrally Planned Countries:	−23,510	−13,535	741,451	+9,731	+22,760
Eastern Europe	−1,474	−330	123,000	+852	+1,395
USSR	−18,198	−10,354	306,989	+8,641	+18,650
China	−3,838	−2,851	311,462	+238	+2,715
III. Developing Countries:	+14,596	+5,212	563,471	−4,257	−7,681
Indonesia	+170	+211	38,956	+190	+213
Thailand	+1,293	+145	27,199	−1,088	−975
Other Southeast Asia	+2	−21	24,742	−29	−6
India	+1,544	+666	174,207	−2,156	−3,208
Other South Asia	+322	−36	61,040	−946	−1,226
High Income North Africa/Middle East	+723	+90	23,895	−422	−701
Low Income North Africa/Middle East	+1,856	+237	62,097	−1,040	−1,750
Middle America	+1,212	+36	36,821	−795	−1,027
Brazil	+2,403	+747	68,754	+40	[illegible]77
Argentina	+5,071	+3,137	45,760	+1,989	[illegible]6
IV. Total above	−7,111	−8.117	1,987,904	−5,055	−[illegible],471
(% world production)	−.34%	−.43%		−.24%	−.07%
V. Warming Countries' Total[1]	−32,190	−17,250	—	+10,613	+26,559
VI. Cooling Countries' Total[2]	+25,079	+9,133	—	−15,668	−28,030

[1] Countries favorably impacted by warming (Canada, E. Europe, USSR, China).

[2] Countries favorably impacted by cooling (U.S., Eur. Community, Other Western Europe, Australia, South Africa, Indonesia, Thailand, Other S.E. Asia, India, Other S. Asia, High N.Af./M.E., Low N.Af/M.E., Mid. America, Brazil, Argentina).

those whose grain yields are expected to increase if there should be a cooling trend.

Row IV in both tables 4 and 5 indicates that the projected effects of climate change on world grain production are very small indeed. The largest change is for Moderate Cooling, projected to be only a negative 0.45 percent, or approximately 8 million tons, compared to a projected world grain production of 1,988 million tons for the base scenario.

However, the world is not *one* world when it comes to sharing in the effects of variations in world grain production.[6] If free or liberal trade policies were followed with respect to grain by the nations of the world, the production variations indicated in table 4 would have negligible effects on grain prices—the maximum effect would be about 1 percent. Most countries of the world do not permit their domestic grain prices to reflect the changes in the prices at which grain is traded among nations.

INTERNATIONAL TRADE IN GRAINS

Table 6 gives the projected quantities of grain exported or imported under the five scenarios for selected countries or regions for the year 2000. The quantities represent net trade, since countries or regions may export some kinds of grain while importing other kinds. The sums of the regional trade data included in table 6 do not add to total world exports or imports because, as noted above, areas of Africa, Latin America, and East Asia were excluded from the scenarios.

The results in table 6 necessarily depend on assumptions concerning the trade policies of the different regions. With regard to the United States, Canada, and Australia, for example, we assumed that grains would be exported without restraint and that domestic prices would be directly related to export prices.

For the Soviet Union, we assumed that virtually all variations in grain production would be offset by variations in net trade. This assumption is a reasonable approximation to the policy followed by the Soviet Union during the 1970s. It implies that the Soviet Union does not modify the level of consumption significantly from year to year on the basis of variations in its own level of grain production. Although this may be a reasonable policy in response to annual variations in production, it might not be the Soviets' reaction to long-run changes in production brought about by climate change. The level of Soviet grain imports projected for Large Cooling could be managed, if so desired, since the annual import cost (assuming

Table 5

VARIATIONS IN GRAIN PRODUCTION (PERCENT) FROM BASE PROJECTION LEVELS UNDER ALTERNATIVE CLIMATE SCENARIOS

(Expected Value Estimate of Impact of Climate Change on Crop Yields)

Crop/country	Scenarios				Historic inter-annual variation[1]
	Large cooling	Moderate cooling	Moderate warming	Large warming	
	Percent variation from Base 2000 levels				
I. Developed Countries:	.3	.1	−1.5	−2.4	±9.1
United States	1.5	1.2	−2.0	−3.8	±9.2
Canada	−13.7	−5.9	1.4	6.0	±13.4
European Community	.3	−.9	−1.8	−2.2	±5.8
Other Western Europe	.6	−.6	−1.6	−2.0	±7.1
Australia	4.8	−.5	−.6	−3.0	±14.5
South Africa	11.2	3.7	−1.9	−4.1	±20.2
II. Centrally Planned Countries:	−3.2	−1.8	−1.3	3.1	±10.7
Eastern Europe	−1.2	−.3	.7	1.1	±8.4
USSR	−5.9	−3.4	2.8	6.1	±16.1
China	−1.2	−.9	.1	.7	±6.6
III. Developing Countries:	2.6	.9	−.8	−1.4	±7.7
Indonesia	.4	.5	.5	.5	±4.5
Thailand	4.8	.5	−4.0	−3.6	±9.4
Other Southeast Asia	.0	−.1	−.1	−.0	±5.0
India	.9	.4	−1.2	−1.8	±7.6
Other South Asia	.5	−.1	−1.6	−2.0	±6.1
High Income North Africa/Middle East	3.0	.4	−1.7	−2.8	±9.6
Low Income North Africa/Middle East	3.0	.4	−1.8	−2.9	±10.5
Middle America	3.3	.1	−2.2	−2.8	±7.1
Brazil	3.5	1.1	.1	.3	±4.7
Argentina	11.1	6.7	4.3	2.6	±11.7
IV. Total Above	−.4	−.4	−.3	−.0	±9.5
V. Warming Countries' Total[1]	−4.0	−2.1	1.3	3.3	±10.9
VI. Cooling Countries' Total[2]	2.8	1.0	−1.7	−3.1	±9.0

[1] Countries favorably impacted by warming (Canada, E. Europe, USSR, China).

[2] Countries favorably impacted by cooling (U.S., Eur. Community, Other Western Europe, Australia, South Africa, Indonesia, Thailand, Other S.E. Asia, India, Other S. Asia, N.Af/M.E., Mid. America, Brazil, Argentina).

Table 6

VARIATIONS IN GRAIN TRADE FROM BASE PROJECTION LEVELS UNDER ALTERNATIVE CLIMATE SCENARIOS[1]

(Expected Value Estimate of Impact of Climate Change on Crop Yields)

Country/Region	Large cooling change	Moderate cooling change	Projected base level	Moderate warming change	Large warming change
			Million metric tons		
I. Exporters:					
U.S.	+9.6	+10.4	139.2	−2.4	−9.9
Canada	−8.4	−3.3	27.5	+1.2	+4.1
Australia	+1.7	+.1	20.4	−.1	−.7
Argentina	+5.1	+3.1	29.8	+2.0	+1.1
South Africa	+2.5	+.8	5.3	−.5	−1.0
Thailand	+1.3	+.2	7.7	−1.1	−1.0
Brazil	+2.7	+1.3	6.4	+.6	+.3
Total	273.6	271.3	258.0	257.5	255.1
II. Importers:					
Western Europe	−1.1	+1.1	37.2	+3.0	3.9
Soviet Union	+18.2	+10.5	15.0	−8.5[2]	−18.4[2]
High Income North Africa/Middle East	−.7	+.1	24.6	+.5	+.8
Low Income North Africa/Middle East	−1.7	+.1	17.6	+1.4	+2.1
South Asia	−1.6	−.5	9.2	+2.6	+3.8
China	+1.4	+1.1	6.6	−.2[2]	−.6[2]
Total	273.6	271.3	258.0	257.5	255.1
III. Percent Variation From Base	+6.04%	+5.15%	—	−.20%	−1.12%

[1] Grain Trade quoted on a net base for country or region cited.
[2] Minus indicates Soviet and Chinese shift from importing to exporting.

an export price of $200 per ton in 1978 prices) would be less than $1 billion, a relatively small figure considering the projected size of the Soviet economy by the year 2000.

The trade policy assumption for China was also based on recent behavior, namely, that international production changes result in a significant consumption adjustment. It was assumed that China would use trade to compensate for approximately 50 percent of any change in wheat and rice production and 25 percent of any change in coarse grain production.

Significant variations in total grain trade (table 6) for the climate-change scenarios are confined to the United States, Canada, and

the Soviet Union. South Asia and Australia would be affected to a lesser, but still important, degree. As would be expected from the projections of grain production, the United States would have relatively large exports under the two cooling scenarios, while Canada would have relatively small exports for those two scenarios. Conversely, when U.S. exports would be reduced below the base scenario, Canada's exports would be increased. The largest absolute changes in net grain trade would occur in the Soviet Union, with substantial net imports in the Large Cooling scenario and small net exports in the Large Warming scenario. The range exceeds 36 million tons, though this follows directly given the production changes for the Soviet Union and the trade policy assumptions made.

World grain trade is projected to be the smallest for the Large Warming scenario—less than 2 percent below the trade under the base scenario. Trade in the Large Cooling scenario would be a little more than 6 percent larger than under the base scenario.

INTERNATIONAL TRADE PRICES

Table 7 presents the results from the GOL Model for world market grain prices in the year 2000. We emphasize once again that the absolute levels of the prices are not meant to be predictions of expected prices in the year 2000. Our emphasis will be upon the *differences* in prices for the alternative scenarios.

The price variations attributed to climate change are small, being most pronounced for wheat and least for rice. But even for wheat, the highest price increase (Large Cooling) is less than 1 percent in excess of the base price and the greatest price decrease (Large Warming) is little more than 6 percent below the base price. The largest variation for rice price relative to the base scenario is about 1 percent. For all grains, the magnitude and distribution of aggregate yield changes is such as to generate a decrease in price under all the expected-value alternatives—from a 2 percent decrease under Large Cooling to a 4 percent decrease under Large Warming.

SUMMARY OF ECONOMIC EFFECTS

The projected global effects of climate change—within the limits of the four alternative climate-change scenarios—are very small. Barring any economic adjustments, the total yield effects would be small, primarily because the various alternative scenarios would have largely offsetting effects. Some regions would have higher yields if cooling occurred, while other regions would be subjected to lower yields. And the same would be true if warming occurred; some regions would gain and others would lose.

Table 7

VARIATIONS IN WORLD MARKET GRAIN PRICES FROM BASE PROJECTION LEVELS UNDER ALTERNATIVE CLIMATE SCENARIOS[1]

(Expected Value Estimates of Impact of Climate Change On Crop Yields)

Commodity	Large cooling change	Moderate cooling change	Projected base level	Moderate warming change	Large warming change
		1969–71 U.S. $ per metric ton			
Wheat	+.64	−1.90	93.42	−4.83	−6.11
Coarse Grain	−2.34	−4.35	90.62	−4.76	−4.89
Rice	+4.74	+5.09	374.09	+3.59	+2.17
All Grain Total[2]	−2.20	−4.13	114.36	−4.44	−4.94
Percent Variation From Base 2000	−1.92%	−3.61%	—	−3.88%	−4.32%

[1]See bottom of model print-outs for product and price specifications and base 1969–71 prices.
[2]Weighted by volume in international trade.

It may be useful to put into perspective the relative importance of climate change in affecting world grain production. A 10 percent change in either per capita income or population growth rates would generate roughly four times as large a change in world grain production as would be generated by either the Large Cooling or the Large Warming scenarios. Such a change in income or population growth rates would be well within the range of the World Bank's or the U.S. Census Bureau's high and low projections that were the bases of the income and population variables used in the GOL Model. This comparison is not intended to indicate that climate is without importance. Rather, the comparison is intended to indicate that many factors—technology and research; the availability of adequate fertilizer supplies; and the rate of investment in agriculture infrastructure, including water management schemes—will likely affect grain production at the turn of the century to a greater extent than will the small climate changes identified in Task I. The difference between the weighted mean of the U.S. corn yields ascribed to technological change by the respondents in Task II and the projection used in the GOL Model would appear to have a substantially greater impact on world grain production than would any of the climate scenarios.

CHAPTER THREE

THE ESTIMATED EFFECTS OF ALTERNATIVE CLIMATIC ASSUMPTIONS

INTRODUCTION

Four climate-change scenarios were included in the analysis on the basis of the expected yields derived from the results of Task II. To indicate the possible effects of extreme variations in climate, several additional computer runs were made with the GOL Model. These runs included two sets that were based upon the annual-yield distributions developed in Task II for each of the four climate-change scenarios. In one set the expected yields were *replaced* by the 25th percentiles of the distributions, and in the other set the yields were taken to be the 75th percentiles. The yields at the 25th percentile represent the maximum yields at or below that percentile, while the 75th yields are the minimum yields at or above that percentile.

In another pair of runs, we assumed that precipitation would be either 10 percent higher or lower than the expected level for the base scenario. As it turned out, the higher precipitation levels gave approximately the same results as the run with the 75th-percentile yields, and the results at the lower precipitation level were similar to those with the 25th-percentile yields.

PROBABILITIES OF OCCURRENCE

Each alternative run is for a projected event with very low probability. We cannot give a precise estimate of the probabilities since we cannot assume independence in the factors that would result in all the yields being at the 25th percentile or the 75th percentile for the various country-crop combinations. However, exhaustive tests on world grain production data indicate covariances near zero for locations separated by more than 500 miles. The same results have been obtained from similar tests on precipitation data. A comparison of the yield variations projected for the 25th- and 75th-percentile runs with the coefficient of variation of world grain yields for 1950–77 supports the conclusion that the probabilities are low. Compared to the base climate scenario projection, the projected yields for the 75th percentile are 8 to 10 percent higher and for the 25th percentile, 8 to 9 percent lower. The coefficient of variation for actual grain yields for 1950–77 was 3.1 percent. Consequently, a

yield departure from trend level greater than 9.3 percent would be expected only once in 1000 years.

GRAIN PRODUCTION

In terms of total world grain production, the largest deviation from the base level for any of the climate scenarios at their expected-yield estimates was 0.43 percent. By contrast, the largest deviation between the expected-yield estimate for the base scenario and for the 25th-percentile run was −4.7 percent; for the 75th-percentile runs, it was +3.7 percent. The runs for a 10 percent increase in precipitation indicated a 1.9 percent increase in grain production, while the 10 percent precipitation decrease resulted in a 3.3 percent reduction.

In the four main climate-change scenarios, the projected climate-induced changes in grain production are significantly smaller than the projected changes in grain yields for each of the alternative runs. As was the case for the expected-yield estimates, the production projections from the GOL Model reflect the effects of market price changes on the inputs that would be devoted to grain production. A reduction in yields—as in the 25th-percentile runs—results in higher prices and expansion of the area devoted to grains, as well as an increase in inputs such as fertilizer that positively affect yields. Lower grain prices, such as would result from the 75th-percentile grain yields, would reduce both the grain area and the quantities of yield-increasing inputs used.

GRAIN TRADE AND PRICES

These seemingly small production deviations were projected to have significant effects on trade flows and international market prices. The 75th-percentile and the +10 percent precipitation runs projected substantial declines in world trade flows, with the United States bearing a substantial fraction of the reduction in all cases.

Substantial changes in world market grain prices were projected in the 25th-percentile and −10 percent precipitation runs. The largest increase in market price is 65 percent for all grains in the 25th-percentile Large Warming change; the smallest increase in this set of runs is 27 percent for the Large Cooling change. The run for the 10 percent decline in precipitation falls in an intermediate position at 37 percent.

The 75th-percentile and the +10 percent precipitation runs result in an increase in total world grain production and in relatively modest declines in world market prices of grain ranging from 9 to 14 per-

cent. The primary reason for the lower relative magnitudes of price effects from increased production is the greater response of production to price declines than to price increases, combined with the low price elasticities of demand for food grains.

The projected price for rice increases compared to the base projection is relatively small, in the range of 5 to almost 10 percent. The largest changes are for wheat, and one run indicates an increase of almost 80 percent.

GRAIN USAGE IN THE 25TH-PERCENTILE RUNS

A comparison of the incidence of the shortfalls in grain usage resulting from the lower production levels in the 25th-percentile runs may be of interest. Although the largest production shortfall compared to the base projection is for the Large Cooling change, the greatest increase in world market grain prices is for the Large Warming change. The primary reason for this increase is that U.S. grain production is significantly lower than in the Large Cooling change. Whereas world production is about 12 million tons larger in Large Warming than in Large Cooling, U.S. Large Warming production is 29 million tons less than the Large Cooling production. Most of the additional grain production under the Large Warming scenario, compared to the Large Cooling scenario, is projected to occur in countries or regions that control international trade in grains to meet national objectives with *little or no concern* for the effects on the rest of the world.

Table 8 compares the projected grain usage for the year 2000 for the United States, other developed countries, centrally planned economies, and developing countries for the four 25th-percentile runs and the base run.

Table 8

PROJECTED GRAIN USAGE BY MAJOR REGIONS IN THE YEAR 2000 FOR BASE AND 25th-PERCENTILE RUNS

(In millions of tons)

	Base Run	Large Cooling	Moderate Cooling	Moderate Warming	Large Warming
United States	250	239	232	231	231
Other Developed	337	323	314	312	309
Centrally Planned	775	714	755	757	756
Less Developed	712	702	697	694	696
Total	2,074	1,979	1,998	1,999	1,993

IMPACT OF THE "WORST" CASE ON THE DEVELOPING COUNTRIES

Total grain usage for the 25th-percentile Large Warming scenario is projected to be 4 percent lower than in the base scenario. The United States and other developed economies would have 8 percent reductions, whereas the centrally planned economies and the less developed regions would have reductions of 2.5 percent or less. The impact of a 2.5 percent reduction in grain usage in the less developed regions would be significant, but it does not seem to be so large that the countries could not adapt to it by various adjustments, including some reduction in marketing and storage losses, a modest increase in milling rates for grain, and a greater investment in research to increase yields under the predicted climatic conditions.

Since the developing regions are net importers of grain, their grain import bill would be substantially increased if the assumptions of the 25th-percentile yields for the Large Warming scenario were to prevail. Under the Large Warming scenario, gross grain imports are projected at 145 million tons; under the base scenario, 134 million tons. These import levels are many times larger than the 32 million tons of gross imports in 1970 with exports of 14 million tons. The gross import bills would be, respectively, $26 billion and $15 billion. (Note that these calculations ignore the approximately 58 million tons of grain exports by the developing countries.) The prices used in these calculations are in terms of 1969–71 averages.

Would the projected $11 billion increase in the grain import bill be manageable? Two considerations should be taken into account. First, if grain prices were at the level projected, the prices of other internationally traded agricultural products would almost certainly be higher under the 25th-percentile Large Warming scenario than under the base scenario conditions. By the year 2000 the present developing countries should still be substantial exporters of agricultural products, though by then most of the developing countries should be exporting more manufactured than agricultural products.

Second, the increase in the cost of grain imports for the low-income and low-middle-income developing countries in the year 2000 would be approximately $3 per capita (in 1970 dollars). The per capita gross national product in these countries would be about $350 if per capita incomes grow by 2.5 to 3.0 percent annually. For this group of countries, which does not include all of the developing countries classified in the GOL Model as developing countries, the increase in the grain import bill due to the higher international grain prices and the increased quantity of imports projected for the 25th-percentile Large Warming scenario would be $9 billion.[7]

Obviously, the increased grain import bill would not be the only adverse effect upon the developing countries. Grain usage, as indicated in table 8, would decline by 2.3 percent or about 5 kilograms per capita, from 203 to 198 kilograms. Per capita consumption in 1970 was 172.5 kilograms.

The incidence of the production and usage shortfalls of the 25th-percentile Large Warming case would not be uniform among developing countries according to the results of the GOL Model. India's production would be 8.5 percent below the base level; Other South Asia, 6.1 percent; and North Africa, more than 10 percent. Brazil is projected to have production more than 8 percent higher, and Indonesia, Thailand, and Other Southeast Asia would be affected very little.

One should not be sanguine about the effect of grain yields in the lower range of the distributions estimated by Task II, but if a reasonable rate of economic growth occurs between now and the year 2000, the consequences could hardly be described as catastrophic. There is little doubt some disruption would take place if the climate change to which we have assigned a probability of 2.5 percent should occur. How disruptive this event would be, if it should occur, would depend more on the growth of per capita grain and food production between now and the year 2000 than on the projected 4 to 5 percent decline in grain production associated with the 25th-percentile grain yields compared to the base yields. An increase in the annual rate of growth of grain production of less than 0.2 percent would fully offset the effects of the yields falling in the lower end of the distributions.

CHAPTER FOUR

IMPLICATIONS FOR DOMESTIC AND INTERNATIONAL POLICIES

INTRODUCTION

The expected-yield estimates for the four climate-change scenarios indicate that for the world as a whole the effects of the assumed climate changes are largely offsetting. Not only are the effects of each climate scenario on total grain production expected to be very small, but the effects on international grain prices are also very small. Consequently, few domestic or international policy implications need to be considered.

MAJOR PRODUCERS AND TRADERS

Some individual countries or regions might well see production and trade effects of climate change that are significant enough to warrant some policy changes. The United States, however, does not seem to be one of these countries since the largest expected declines in production and exports are 3.8 and 7.1 percent, respectively, for the Large Warming scenario.

However, Canada and the Soviet Union might well find it necessary to adjust their policies if the Large Cooling scenario were to prevail. The production and trade effects would be large enough to require regional resources adjustments within agriculture or substantial investments in research to develop grain varieties that would be less adversely affected by cooler temperatures.

DEVELOPING COUNTRIES

The large developing countries would appear not to be significantly adversely affected by climatic changes on the order of the four Task II scenarios. Thus the envisioned changes in climatic conditions would not call for any significant change in food-aid shipments or in general economic assistance. The developing countries that imported grain would face approximately the same prices under the four climate-change scenarios as in the base case.

Under the highly improbable cases of the 25th-percentile yields or a 10 percent decline in precipitation, some changes in international policies should be considered to minimize adverse effects on developing countries. As argued earlier, even though the 25th-percentile

yields would not have catastrophic or unmanageable impacts on developing countries, for some developing countries such yields would result in an increase in the share of food expenditures in the gross national product and would slow down economic growth by reducing investment. This would seem to be the situation confronting India, the low-income countries of North Africa and the Middle East, and Other South Asia.

The policy changes that would be effective in assisting the group of developing countries most adversely affected by the 25th-percentile yields, should they occur, include liberalizing trade in agriculture products so that the reductions in world grain production would be more equitably shared and international grain prices would be lowered, and increasing research expenditures to help these countries increase their own production. If year-to-year production variability were to be the same as the historical pattern or to increase, food-aid shipments should be managed to assist these countries to offset the variability in their own grain production.

CONCLUSIONS

This study concludes that no major climatic changes are anticipated by the end of this century and the small changes that might occur will minimally affect production and international prices. We should, however, be concerned about the level of food production and consumption in the developing countries, especially the low-income developing countries. The desirability of significant research to increase both food production and per capita incomes in the developing countries has not been diminished by the results of this study. The need for a more rapid rate of growth in food production in the developing countries deserves serious and continuing attention.

ENDNOTES

1. See *Climate Change to the Year 2000, A Survey of Expert Opinion* (Washington, D.C.: National Defense University, 1978).

2. See *Crop Yields and Climate Change to the Year 2000,* 2 vols. (Washington, D.C.: National Defense University, 1980, 1982).

3. The tips of the arrows in figure 2 mark the standard deviations of annual temperature and precipitation observed in the base period. The polygon encloses the most likely crop-weather events. If one assumes that the bivariate distribution of recorded base period crop weather is normal, then there is a probability of 0.954 that the temperature and precipitation of a randomly selected year will fall inside the polygon.

4. The Grain-Oilseed-Livestock Model is described in the following publications: *Alternative Futures for World Food in 1985,* vol. 1, Analytical Report; vol. 2, Supply-Distribution and Related Tables; vol. 3, Structure and Equations. USDA/ESCS/Foreign Agriculture Economic Report Nos. 146, 148, 151.

5. For a list of the countries included in table 3 and their classification into the three categories of developed, centrally planned, and developing, see Appendix A.

6. World market prices have relatively little influence on production and consumption decisions for most of the world's producers and consumers. Consequently, small world-grain production variations can have substantial effects on world market prices and on domestic prices in countries whose domestic prices are closely linked to world market prices, as in the United States. A large fraction— perhaps as much as half—of the large increase in international grain prices between 1972 and 1974 was due to effects of national policies that stabilized internal prices and consumption even though world grain production declined. See D. Gale Johnson, "World Agriculture, Commodity Policy, and Price Variability," *American Journal of Agricultural Economics,* 57(5): 823–28.

7. The countries and areas excluded from the developing country category were Argentina, Brazil, high-income North Africa and Middle East, and high-income East Asia. The countries included have per capita gross national products (in 1970 dollars) in 1976 of $750 or less—an average of approximately $180. The projected population for the year 2000 of the included developing countries was 2,800 million. Income data, population, and income population projections were derived from *World Development Report, 1978,* The

ENDNOTES

World Bank, August 1978. The projected grain imports for the included developing countries for the base scenario case projection were 83 million tons; for the 25th-percentile Large Warming scenario projection, they were 101 million tons. The prices per ton (in 1970 dollars) were $109 and $179, respectively. Total grain import bills were projected at $9 billion for the base scenario and $18 billion for the 25th-percentile Large Warming scenario.

APPENDIX A
COUNTRY COMPOSITION OF CATEGORIES IN THE WORLD GRAIN-OILSEED-LIVESTOCK MODEL

Regions	Composition
I. Developed countries	
United States	United States
Canada	Canada
EC–6	Belgium, France, West Germany, Italy, Luxembourg, Netherlands
EC–3	Denmark, Ireland, United Kingdom
Other Western Europe	Austria, Finland, Greece, Iceland, Malta, Norway, Portugal, Spain, Sweden, Switzerland
Japan	Japan
Oceania	Australia, New Zealand
South Africa	Botswana, Lesotho, Namibia, Republic of South Africa, Swaziland
II. Centrally planned countries	
Eastern Europe	Albania, Bulgaria, Czechoslovakia, East Germany, Hungary, Poland, Romania, Yugoslavia
Soviet Union	Soviet Union
China	People's Republic of China
III. Developing countries	
Middle America	Mexico, Bahamas, Bermuda, Costa Rica, Dominican Republic, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Trinidad & Tobago, Other Caribbean Islands
Argentina	Argentina
Brazil	Brazil
Venezuela	Venezuela
Other South America	Bolivia, Chile, Colombia, Ecuador, French Guiana, Guyana, Paraguay, Peru, Surinam, Uruguay

GOL MODEL CATEGORIES

Regions	Composition
High-income North Africa and Middle East	Algeria, Bahrain, Cyprus, Iran, Iraq, Israel, Kuwait, Libya, Oman, Qatar, Saudi Arabia, United Arab Emirates
Low-income North Africa and Middle East	Egypt, Jordan, Lebanon, Morocco, Sudan, Syria, Tunisia, Turkey, Yemen (Aden), Yemen (Sana)
East Africa	Kenya, Malagasy Republic, Malawi, Mozambique, Rhodesia, Tanzania, Uganda, Zambia
Central Africa	Angola, Burundi, Cameroon, Central African Empire, Chad, Congo, Ethiopia, Djibouti, Benin, Gabon, Gambia, Ghana, Guinea, Equatorial Guinea, Guinea-Bissau, Ivory Coast, Liberia, Mali, Mauritania, Mauritius, Niger, Nigeria, Reunion, Rwanda, Senegal, Sierra Leone, Somalia, Togo, Upper Volta, Zaire
India	India
Other South Asia	Afghanistan, Bangladesh, Bhutan, Nepal, Pakistan, Sri Lanka
Thailand	Thailand
Other Southeast Asia	Burma, Cambodia, Laos, South Vietnam
Indonesia	Indonesia
High-income East Asia	Hong Kong, Singapore, South Korea, Taiwan, Brunei
Low-income East Asia	Malaysia, Philippine Islands
Rest of the World	North Korea, North Vietnam, Mongolia, Cuba, Pacific Islands, Papua-New Guinea

APPENDIX B
A SUMMARY OF CROP YIELDS AND CLIMATE CHANGE TO THE YEAR 2000

INTRODUCTION

Some climatologists foresee a cooler earth by the turn of the century, while others see a warmer one. In 1976 the Research Directorate of the National Defense University organized a cooperative study to quantify such judgments and assess the impact of the perceived climate changes on agriculture. The main objectives of the study were embodied in three tasks:

- Task I. To define and estimate the likelihood of changes in climate during the next 25 years, and to construct climate scenarios for the year 2000.
- Task II. To estimate the likely effects of possible climatic changes on selected crops in specific countries, and to develop a methodology for combining crop responses and climate probabilities into climate-crop scenarios for the year 2000.
- Task III. To evaluate the domestic and international policy implications of the climate-crop scenarios, and to *identify the climate variables that are of key importance* in the choice of policy options.

The results of Task I were published in *Climate Change to the Year 2000, A Survey of Expert Opinion,* by the National Defense University in February 1978. This summary is concerned with Task II and the italicized portion of Task III.

Task II was accomplished by means of a simple, discrete climate-response model of apparently broad applicability. To project the effects of an assumed climate change on a particular crop, the model combines two matrices; one matrix expresses relative annual yield as a function of mean temperature and precipitation. The primary output of the model is a frequency distribution of relative annual yields that reflects the year-to-year variability of temperature and precipitation in the assumed climate state. The annual-yield matrix is based on estimates solicited from a panel of agricultural scientists, and the crop-weather matrix is based on climatological records.

The model isolates the climate component of crop yields by assuming a constant agricultural technology. To help the panelists put aside the dynamics of technology before they addressed weather-yield relationships for a crop, we asked them to project separately the effects of technology on yield trends assuming no change in climate between 1976 and 2000. Although technology was a secondary issue in the context of Task II, the technology component of crop yields is a subject of great importance. Indeed, one of our principal conclusions is that technology, rather than climate, is likely to be the chief determinant of most crop yields in the last quarter of the 20th century.

METHODOLOGY: THE CLIMATE COMPONENT OF CROP YIELDS

The climate-response model projects frequency distributions of annual crop yields for arbitrary climate states, which are compared to the climate of the recent past (the base period). In calculating these distributions, we assumed no change from the indigenous technologies of 1976.

The model was applied to the 15 "key" country-crop combinations in table S–1. Peculiar to each combination is a matrix whose elements express relative annual yield Y as a function of ΔT and ΔP, where

ΔT = the departure of a year's mean heading-period temperature from the long-term average prevailing in the base period, and

ΔP = the percentage departure of the same year's mean crop-year precipitation from the long-term average prevailing in the base period.

To be more precise, the annual crop-weather points (ΔT, ΔP) are midpoints of rectangular regions in the temperature-precipitation plane. The same yield value $Y(\Delta T, \Delta P)$ is ascribed to all joint weather events that lie in the rectangle centered on the point (ΔT, ΔP). All three variables are considered to be spatial averages for the crop region of interest. The annual-yield matrix is itself an expertise-weighted average of individual matrices submitted by members of the Agriculture Panel. One of the aggregated annual-yield functions is graphed in figure 2.

Associated with each annual-yield function $Y(\Delta T, \Delta P)$ is a climatological probability density function. The latter is a bivariate normal distribution (BND) that approximates the joint distribution of ΔT and ΔP observed in the base period. The duration of the base period varies from crop to crop according to the length of the available

Table S-1

THE EXPECTED CLIMATE CHANGES ASSUMED TO AFFECT THE KEY CROPS IN THE FIVE GLOBAL CLIMATE SCENARIOS

		KEY CROPS					CLIMATE SCENARIOS: EXPECTED CHANGES IN ZONAL TEMPERATURE ($\Delta\bar{T}$°C) AND PRECIPITATION ($\Delta\bar{P}$%)									
							LARGE COOLING (LC)		MODERATE COOLING (MC)		SAME AS THE LAST 30 YEARS		MODERATE WARMING (MW)		LARGE WARMING (LW)	
Zone of Latitude	Hemisphere	CORN	RICE	SOYBEANS (SYBN)	SPRING WHEAT (SPWT)	WINTER WHEAT (WNWT)	$\Delta\bar{T}$	$\Delta\bar{P}$	$\Delta\bar{T}$	$\Delta\bar{P}$	$\Delta\bar{T}$	$\Delta\bar{P}$	$\Delta\bar{T}$	$\Delta\bar{P}$	$\Delta\bar{T}$	$\Delta\bar{P}$
HIGHER MIDDLE 45° - 65°	N				CANADA U.S. USSR	USSR	-1.05	-2.0	-0.50	-2.0	+0.25	0.0	+0.65	+2.0	+1.40	+6.0
LOWER MIDDLE 30° - 45°	N	U.S.		U.S.		PRC U.S.	-0.85	+2.0	-0.35	0.0	+0.25	0.0	+0.45	0.0	+1.00	+2.0
	S	ARG*				ARG* AUS*	-0.95	+2.0	-0.20	0.0	+0.15	0.0	+0.45	0.0	+1.00	+2.0
SUB-TROPICAL 10° - 30°	N		INDIA PRC			INDIA	-0.50	-2.0	-0.30	-2.0	+0.20	0.0	+0.40	0.0	+0.75	+2.0
	S			BRAZIL			-0.50	-2.0	-0.20	-2.0	+0.15	0.0	+0.40	0.0	+0.75	+2.0

* NOTE: ARG = Argentina, AUS = Australia.

climate records from which were extracted the parameters of the BND—the standard deviations of ΔT and ΔP, and their correlation coefficient. The BND is treated as a matrix indexed by ΔT and ΔP; each matrix element BND (ΔT, ΔP) gives the probability that a joint departure of temperature and precipitation will fall in a rectangular region of fixed dimensions centered on the crop-weather point (ΔT, ΔP).

To calculate the probability that an annual yield will lie within a particular interval of yields, one sums the probabilities BND (ΔT, ΔP) such that the corresponding yields $Y(\Delta T, \Delta P)$ lie in the interval. Doing this for a sequence of adjacent yield intervals, one constructs the frequency distribution of annual yields induced by the joint distribution of ΔT and ΔP in the base period. With some obvious liberty, we interpret the base-period BND for each country-crop combination as a description of "present" climate, or the state of "no climate change." However, the base period yield distributions have no direct historical analogs because they are "frozen" in 1976 technology.

In our model, a climate change is a joint occurrence of $\Delta\bar{T}$ and $\Delta\bar{P}$, where

$\Delta\bar{T}$ = change in the long-term average of annual mean heading-period temperature, and

$\Delta\bar{P}$ = percentage change in the long-term average of mean crop-year precipitation,

both changes being referred to the base period. Unlike ΔT and ΔP, the long-term shifts in temperature and precipitation are not restricted to discrete values.

In order to project a distribution of annual yields after a given climate change, we assumed that the pattern of interannual fluctuations of temperature and precipitation about their new averages would be the same as in the base period. This assumption is equivalent to making linear transformation of the random variables in the base period BND. Hence, it is a simple matter to calculate for the given climate change a new crop-weather matrix $\widetilde{\text{BND}}$ (ΔT, ΔP) whose rows and columns are compatible with the annual-yield matrix. Then, summing the probabilities $\widetilde{\text{BND}}$ (ΔT, ΔP) over a sequence of yield intervals, one computes the frequency distribution of annual yields that corresponds to the new climate state. All such frequency distributions employ a uniform scale of "normalized" relative yields on which 100 represents the calculated average yield of a crop in the base period.

Yield distributions were projected for 49 assumed climate changes. We summarized all the distributions for each key crop by plotting their expected values and standard deviations as smooth functions of $\Delta\bar{T}$ and $\Delta\bar{P}$ in the fashion of figure 1. These plots provide a synoptic view of the crop responses to a wide range of climate changes. The likelihood of climate change is a separate consideration.

THE CLIMATE-CROP SCENARIOS

In Task I, after surveying a panel of climatologists, we compiled five global climate scenarios for the year 2000. The climatologists estimated changes in a number of climatic parameters. The individual estimates most relevant to Task II took the form of subjective probability distributions for the global value of $\Delta\bar{T}$ and the values of $\Delta\bar{T}$ and $\Delta\bar{P}$ in certain zones of latitude. Various schemes involving expertise weights were used to aggregate the individual distributions and to derive for each scenario a "probability" of occurrence and a set of "expected" zonal climate changes.

Table S–1 contains the names of the global climate scenarios, the expected zonal climate changes, and the latitude zones of the key crops. The "probabilities" of the scenarios are 0.10 for Large Cooling and Large Warming, 0.25 for Moderate Cooling and Moderate Warming, and 0.30 for the Same as the Last 30 Years scenario (a slight global warming). Roughly speaking, these "probabilities" measure the Climate Panel's collective credence in the *global* temperature change associated with each scenario.

Using the data in table S–1, we calculated frequency distributions of annual yields for each climate scenario. The resulting climate-crop scenarios are discussed in the paragraphs that follow.

METHODOLOGY: THE TECHNOLOGY COMPONENT OF CROP YIELDS

In addition to estimating weather-yield relationships, the Agriculture Panel projected average yields to the year 2000 assuming no change from present climate patterns, but taking into account the likely rate of adoption of new or existing agricultural technology.

A panelist's projection for a single crop consisted of three paths representing the 10th, 50th, and 90th percentiles of yield trends. The triplets of percentiles for the year 2000 were converted to probability density functions, which in turn were weighted according to self-ratings of expertise and then averaged to produce an aggregated frequency distribution of yield estimates. The expected values of these distributions are examined in the next section.

RESULTS: AVERAGE YIELDS AROUND THE YEAR 2000

Salient elements of the climate-crop scenarios and the technology projections are summarized in table S–2. The left-hand portion of the table pertains to the projected average effects of the Task I climate scenarios, assuming no change in technology. (The Same scenario, the most likely of the five, is omitted because its effects on crop yields are negligible.) The middle column pertains to the "expected" effects of technological change, assuming no change in climate.

As for the climate component of yields, one notes that the impact of a particular climate scenario, relative to the base period, differs from crop to crop. Some yields are enhanced (+) by the climate change, others are depressed (−). Among the nine wheat crops, for example, there are five "losers" and four "gainers" in the cooling scenarios. Most crops are antisymmetrical, that is, a cooling scenario and the corresponding warming scenario have opposite and approximately equal effects. "Small" yield changes are in the majority, even in the two extreme scenarios, which have the most pronounced effects.

- The climate changes have the greatest impact in the northern higher middle latitudes, where global temperature changes are amplified. The Canadian and Soviet wheat crops suffer "large" or "moderate" losses in the cooling scenarios and enjoy similar gains in the warming scenarios. U.S. spring wheat responds in the same directions, but its yield changes are "small."

- Next most sensitive after Canadian and Soviet wheat are the key crops of the southern lower middle latitudes, but the directions of their yield responses are contrary to those in the northern higher middle latitudes.

- Yield changes for key crops of the northern lower middle latitudes are "small" in all cases. Changes are in the same directions as in the southern zone, except for Chinese winter wheat, which responds like the more northerly wheat crops.

- In the subtropical latitudes, most yield changes are "small" and negative. Indian wheat has a pattern similar to U.S. winter wheat.

Table S–2 also deals with what we regard as the Agriculture Panel's "best" point estimates of the potential effects of technology, namely, the expected values of the aggregated yield distributions projected for the year 2000. Individually and collectively, the panelists' technology estimates reflect substantial—and understandable—uncertainty about the future adoption of technology for most

Table S-2

PROJECTED EFFECTS OF CLIMATE AND TECHNOLOGY ON CROP YIELDS BY THE YEAR 2000

			CLIMATE SCENARIOS				NO CLIMATE CHANGE	CLIMATE SCENARIOS			
			EFFECT ON EXPECTED YIELDS				EFFECT OF TECHNOLOGY ON EXPECTED YIELDS	EFFECT ON VARIABILITY OF YIELDS			
Zone of Latitude	Hemisphere	Crop and Country	LC p=0.10	MC p=0.25	MW p=0.25	LW p=0.10		LC p=0.10	MC p=0.25	MW p=0.25	LW p=0.10
HIGHER MIDDLE	N	SPWT: *Canada*	- - -	- -	++	+++	24	-	-	+	++
		U.S.	-	-	+	+	26	- -	-	+	+
		USSR	- - -	- -	++	+++	25	-	-	+	-
		WNWT: *USSR*	- - -	- -	++	+++	23	+++	++	- -	- - - -
LOWER MIDDLE	N	CORN: *U.S.*	+	+	-	-	32	- - -	-	++	++
		SYBN: *U.S.*	+	+	-	-	22	- - -	-	++	++
		WNWT: *U.S.*	+	+	-	-	25	- -	-	+	+
		PRC	-	-	+	+	39	- -	-	+	++
	S	CORN: *Arg*	++	+	-	- -	51	- -	-	+	+
		WNWT: *Arg*	++	+	-	- -	32	- -	-	+	+
		Aus	++	+	-	- -	11	- -	-	+	+
SUB-TROPICAL	N	RICE: *India*	-	-	-	-	34	+	+	+	-
		PRC	-	-	-	-	27	-	-	+	+
		WNWT: *India*	+	+	-	- -	29	-	-	+	+
	S	SYBN: *Brazil*	-	-	-	-	40	+	+	+	+

Increase (+) or decrease(-) in the expected (average) annual yield, compared to the Base Period, assuming no change in technology.

CHANGE	SYMBOL	APPROX. RANGE
"SMALL"	*	0% - 3%
"MODERATE"	**	3% - 6%
"LARGE"	***	6% - 9%

Percent increase in the expected (average) yield since 1972-76, assuming no change in climate.

Increase (+) or decrease (-) in the coefficient of variability of annual yields, compared to the Base Period, assuming no change in technology.

CHANGE	SYMBOL	APPROX. RANGE
"SMALL"	*	0% - 8%
"MODERATE"	**	8% - 16%
"LARGE"	***	16% - 24%
"VERY LARGE"	****	24% -

of the key crops. Therefore, the expected values of the technology projections should be seen as very "fuzzy" numbers. The expected technology enhancements are expressed as percentage increases over the average yields of 1972–76 in order to make them commensurable with the expected-yield changes attributable solely to climate change. The climate-neutral technology projections, however, are valid only for the Same scenario.

Setting aside Australian wheat for the moment, we note the following:

- The relative technology increments, ranging from 22 percent to 51 percent, are several times larger than the magnitudes of the respective climate-induced changes.
- U.S. corn excepted, the key crops of Canada, the United States, and the Soviet Union have rather modest technology gains of 26 percent or less.
- All but one of the technology gains ranging upward from 27 percent are registered by the countries that currently have low technology bases—Argentina, Brazil, India, and the Peoples Republic of China.

Returning to Australian wheat, we note that the panelists projected a conspicuously small increase in the technology component of its yields, and that they did so with a relatively high degree of certainty. Their projections manifest a rare consensus: current Australian growing conditions discourage investment in technology inputs. Therefore, one might infer that the panelists would have projected larger technology gains for Australian wheat had they been asked to assume the more benign climates of the cooling scenarios. Climate can affect the rate at which technology is adopted, and technology can modify the response of crops to climate change. Clearly, the interaction of technology and climate merits further study.

RESULTS: THE VARIABILITY OF CROP YIELDS AROUND THE YEAR 2000

The right-hand portion of table S–2 pertains to the projected fluctuations of annual yields as measured by the coefficient of variability (the ratio of the standard deviation to the expected value of a distribution).

The variability of yields is determined by the interplay between the annual-yield matrix and the BND matrix, which describes the year-to-year fluctuations of temperature and precipitation. The integration process involved in the calculation of average yields tends to

smooth out any errors in the two matrices. Most measures of variability, however, are sensitive to errors in both matrices.

In the subtropical latitudes there is a mixed pattern of uniformly "small" relative increases (+) and decreases (−) in the coefficients of variability (CVs). Such responses are to be expected in latitudes where the climate changes and their impacts are small.

In the higher and lower middle latitudes, by contrast, changes in the CVs tend to be greater in magnitude and more regular in direction. About 40 percent of the changes range from "moderate" to "very large," and, with two exceptions, variability decreases or increases accordingly as global temperature decreases or increases. The notable exception is Soviet winter wheat. Qualitatively, its yields become more variable in the cooling scenarios and less variable in the warming scenarios. Quantitatively, in each climate scenario it has the largest relative change in variability.

Two kinds of correlation exist between the changes in expected yields and the changes in variability. For Chinese winter wheat and the three spring wheat crops, the correlation is positive, that is, relative increases or decreases in the average yields of these crops are generally accompanied by like changes in the CVs. For the remaining crops, the correlation is predominantly negative.

In view of the assumed single pattern of crop-weather fluctuations for all climate states, it is noteworthy that the model still projects changes in the variability of annual yields. These changes can be quite striking.

POSSIBLE IMPLICATIONS OF THE YIELD PROJECTIONS

A *quantitative* assessment of climatic effects must be based on agricultural production, which is only partially determined by yield. However, one can draw conditional and *qualitative* inferences from the foregoing yield projections. For example, both Soviet wheat crops are twice-favored by the Large Warming scenario: Not only are the average yields enhanced, but the annual yields become more "dependable." At the same time, all but one of the other key crops have less dependable annual yields, and all but three have lower average yields than in the base period. To a similar degree, the Soviet wheat crops are disadvantaged in the Large Cooling scenario.

Table S–2 suggests that the effects of an extreme climate change on wheat yields in the Soviet Union might alter the Soviets' role in the international grain market and thus indirectly affect their behavior in the political arena as well. The first consideration is whether

their average yields would support adequate production for domestic needs, but this is likely to depend more on technological developments than on climatic change. If average yields were high enough, the Soviet Union could become a net exporter of grain. If average yields were low enough, the country could become a more consistent and heavier buyer of grain. In either case, the variability of its wheat yields would be a secondary matter.

On the evidence of Task II, we can say only that average yields would be considerably higher in Large Warming than in Large Cooling, other things being equal. It is remotely possible, of course, that technological shortfalls would negate the favorable effects of Large Warming on Soviet wheat. Also, in the Large Cooling scenario, technological improvements could enable the Soviets to achieve self-sufficiency in wheat despite the climate handicap.

The variability of yields, which is determined primarily by climate rather than technology, becomes a critical issue when average yields are just adequate or slightly less than adequate. If this were the case, the Soviets would again be better off, economically and politically, in the Large Warming scenario than in the Large Cooling scenario.

These speculations can be extended to second parties. For instance, the Soviets are least likely to be grain buyers in the Large Warming scenario, hence the competition between Canada and the United States for other markets could become acute, given the climatic enhancement projected for Canadian wheat yields. On the other hand, Large Cooling might leave Canada in a poorer position than Argentina, Australia, and the United States to capitalize on potential Soviet wheat requirements.

A PROBLEM OF DETECTION

The results of Task II indicate that by the year 2000, climate-induced changes in average yields are likely to be masked by the larger effects of technological improvements. Hence, we may ask whether changes in the climate component of yields will be discernible at the turn of the century.

Year-to-year fluctuations of yields will also tend to mask any changes in average yields caused by a climate shift. One index of this second masking effect is the ratio of the projected standard deviation of relative annual yields to the distance between the average yield projected by the climate-response model and the average yield calculated for the base period. The ratio is greater than 3.0 for 68 of the 75 scenario-crop combinations, greater than 6.0 for 53

cases, and greater than 12.0 for 37 cases. The remaining seven cases, all of which involve the sensitive Canadian and Soviet wheat crops, have smaller ratios lying between 1.2 and 2.7; they offer the best chances for discriminating climate-induced changes in average yields.

Thus, recognition of the effects of climate change will hinge on filtering out the effects of technology and the "noise" of interannual yield fluctuations. It is apparent that climatic change may have some important agricultural consequences—for individual countries if not for total world food production—but assessment of causes will probably be difficult.

SENSITIVITIES OF THE CLIMATE-RESPONSE MODEL

Of the two weather/climate variables, precipitation emerges as the most important. It is the primary determinant of the variability of annual yields in the base period and is likely to remain so in any of the climate scenarios. Moreover, the projected average yields in the climate-crop scenarios are sensitive to the assumed long-term changes in precipitation. For every country-crop combination, a 10 percent decrease in average precipitation (with no change in average temperature) depresses the expected yield to a greater degree than does the most detrimental climate scenario. And, except for Canadian wheat, a 10 percent increase in average precipitation stimulates the expected yield more than does the most beneficial climate scenario.

We found that *average* yields are not sensitive to 25 percent changes in the standard deviations of ΔT and ΔP. For a given small climate change, we conclude that the average yield (i.e., the expected normalized relative yield) depends primarily on the "shape" of the annual-yield function and not on the BND. Hence, the annual-yield functions are not biased, and the average yields in a climate-crop scenario should be quite accurate—provided, of course, that the expected zonal precipitation changes are consistent with the assumed global temperature changes.

Absolute measures of yield variability are strongly affected by the standard deviation of ΔP but not the standard deviation of ΔT. However, the normalized relative coefficient of variability (NRCV)—the ratio of the CV after a climate change to the CV in the base period—is rather insensitive to the standard deviations of ΔT and ΔP. This *relative* measure of variability is determined by the relationships among the particular climate change, the annual-yield function, and the correlation coefficient used in the BND. We have more confidence in the projected NRCVs, the bases of table S–2, than we do in the ordinary coefficients of variability.

CAVEATS

The preceding discussion concerns not fact but the output and behavior of a climate-response model. Our findings are affected by the simplicity of the model, which has only two highly aggregated weather/climate variables, and by a number of assumptions. The results are also subject to uncertainties about the annual-yield functions and the expected zonal climate changes in the climate scenarios, especially the considerable uncertainties about the expected precipitation changes. The uncertainties affecting the technology projections are obvious.

Even if they were "correct" in every respect, the two types of yield projections would have to be interpreted with care. First, we have not accounted for the *combined* effects of climatic change and technological change on crop yields. Second, we must heed the distinction between absolute yields and relative yields. The former are the currency of the technology projections, the latter of the climate-response model.

The "validity" of the model is an intricate question because the effects of technology, economics, and agricultural policy must be removed from recorded yields before we can compare them with the yield distribution calculated for the base period. Such factors have a marked effect on the variability of historical yields, but they are absent from the uncalibrated model. Thus real-life complications may thwart a straightforward validation test based on an absolute measure of variability like the CV. Nevertheless, the projected normalized relative CVs could be fairly accurate if technology and other factors remained constant.

Our confidence in the climate-response model rests mainly on its cogency, its lack of sensitivity to certain parameters, and the consistency of its outputs. As for the "soft" inputs to the model—the annual-yield functions and the five climate scenarios—the case rests partly on the expertise of the panelists and partly on the techniques used to aggregate their estimates. If readers take exception to our particular climate scenarios, they can invent their own and assess their consequences with the materials provided in *Crop Yields and Climate Change to the Year 2000.* Ideas for improving the study are included in the detailed report.